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Diffusive synchrotron radiation from extragalactic jets

G. D. Fleishman[1,2]⋆
[1] *National Radio Astronomy Observatory, Charlottesville, VA 22903, US*
[2] *Ioffe Institute for Physics and Technology, St.Petersburg, 194021, Russia*

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ABSTRACT

Flattenings of nonthermal radiation spectra observed from knots and interknot locations of the jets of 3C273 and M87 in UV and X-ray bands are discussed within modern models of magnetic field generation in the relativistic jets. Specifically, we explicitly take into account the effect of the small-scale random magnetic field, probably present in such jets, which gives rise to emission of Diffusive Synchrotron Radiation, whose spectrum deviates substantially from the standard synchrotron spectrum, especially at high frequencies. The calculated spectra agree well with the observed ones if the energy densities contained in small-scale and large-scale magnetic fields are comparable. The implications of this finding for magnetic field generation, particle acceleration, and jet composition are discussed.

Key words: acceleration of particles – shock waves – turbulence – galaxies: jets – radiation mechanisms: non-thermal – magnetic fields

1 INTRODUCTION

Relativistic extragalactic jets are known to provide very efficient acceleration of relativistic electrons up to Lorentz-factors $\gamma \sim 10^6 - 10^7$ or higher (Heavens & Meisenheimer 1987). Quasi-exponential cut-offs found in many synchrotron sources in the infrared (IR), optical, or ultraviolet (UV) bands (Rieke et al. 1982; Röser & Meisenheimer 1986; Meisenheimer & Heavens 1986; Keel 1988) are in a good agreement with the idea of a maximum energy of accelerated electrons, which results from the balance between the efficiency of the acceleration mechanism and synchrotron losses.

The presence of a high-energy cut-off in the energetic spectrum of relativistic electrons results naturally in a progressive spectral softening as the frequency increases in the region of the synchrotron cut-off, which indeed has been observed. However, recent observations (Jester et al. 2005) of the radio-to-UV spectra of the jet in 3C273 performed with the highest angular resolution achieved so far (0".3) revealed significant flattening of the radiation spectra in the UV band from most of the jet locations, including both knots and inter-knot regions.

This finding of an additional UV spectral component cannot be easily accommodated within models of synchrotron emission produced by a single population of relativistic electrons (Jester et al. 2005) and requires either a distinct secondary component of relativistic particles, and/or a different radiative process, dominating the UV excess. Either of these possibilities suggests that jet models should include additional physical processes involving particle acceleration or the radiation mechanism. Given similar spectral behavior found in the jet of M87 in the optical to X-ray transition (Perlman et al. 2001; Marshall et al. 2002; Waters & Zepf 2005), this problem seems to be of a general interest for jet physics.

The idea of a secondary population of the relativistic electrons is discussed in some detail by Jester et al. (2005) who show that it imposes rather stringent new requirements on the acceleration mechanism involved. Here we envision an alternate possibility predicted theoretically almost 20 years ago (Toptygin & Fleishman 1987a): that the observed spectral flattening in certain jets is an *intrinsic property* of the *emission mechanism*. Specifically, we explore the consequences of the presence of small scale random magnetic fields for the synchrotron radiation mechanism. Observational evidence that such fields exist in the jet volume has been discussed by Hughes (2005) and references therein. Moreover, recent models of magnetic field generation in relativistic sources in general (Kazimura et al. 1998; Medvedev & Loeb 1999; Nishikawa et al. 2003, 2005; Jaroshek et al. 2004, 2005; Hededal & Nishikawa 2005), and in extragalactic jets in particular (Honda & Honda 2002, 2004), predict that the random magnetic field produced is extremely small-scale, with a typical correlation length as small as the plasma skin depth or less, which can be less than the coherence length of synchrotron emission:

$$l_s = \frac{mc^2}{eB} = \frac{c}{\omega_{Be}}. \quad (1)$$

⋆ E-mail: gregory@sun.ioffe.ru

Here, e and m are the electron charge and mass, and $\omega_{Be} = eB/mc$ is the electron gyrofrequency. Generation of electromagnetic emission by relativistic electrons moving in small-scale magnetic fields is known to differ from the case of emission by electrons in a uniform (large-scale) magnetic field (Landau & Lifshitz 1971).

In this paper, therefore, we address the question of whether the presence of the small-scale random magnetic field in the jet volume can account for the observed high-frequency excesses in the jet spectra, and conclude that the small-scale field with a level comparable with the level of large-scale field is indeed naturally capable of providing the observed spectral flattening.

2 DIFFUSIVE SYNCHROTRON RADIATION

The effect of the spatial scale of the magnetic field on the corresponding electromagnetic radiation produced by fast electrons is provided by non-local nature of the emission. Indeed, the elementary emission pattern of the synchrotron radiation is accumulated over a finite part of the particle trajectory of the order of the coherence length l_s. Accordingly, if the magnetic field experiences variations over this length, the particle trajectory deviates from a circular trajectory, which results in a radiation spectrum rather different from one formed in the uniform or large-scale magnetic field. We will refer the synchrotron radiative process in the presence of small-scale magnetic fields as *Diffusive Synchrotron Radiation* (DSR), since the particle random walks due to its interaction with the random field.

The theory of DSR was developed some time ago by Toptygin et al. (1987) and Toptygin & Fleishman (1987a); see also the recent review and developments by Fleishman (2005, 2006). When both large-scale regular and small-scale random fields are present in a volume, the resulting radiation spectrum is composed of two contributions. One component results from the large-scale field and is essentially the normal synchrotron spectrum. The second component is DSR (called also "3D jitter radiation", Hededal (2005)) resulting from the interaction of the ultrarelativistic electrons with small-scale random fields. If the distribution of ultrarelativistic electrons is characterized by a maximum Lorentz factor γ_m, first component dominates for frequencies $f < f_{Be}\gamma_m^2$, where $f_{Be} = \omega_{Be}/2\pi$, while for frequencies $f > f_{Be}\gamma_m^2$, the synchrotron spectrum decreases exponentially with frequency, and the contribution of DSR becomes the dominant one.

The effect of small-scale magnetic inhomogeneities on the radiation spectrum produced by a relativistic electron is caused by the change in the electron trajectory compared with the regular gyration it would experience in a large-scale magnetic field. In the presence of a random field superimposed on the regular field, the particle trajectory experiences random fluctuations superimposed on the regular motion. In essence, these fluctuations represent an incoherent superposition of oscillations with various frequencies/wavelengths. Because of relativistic transformation, each of these elementary oscillations with the scale $l = 2\pi/k$ results in emission at the frequency $\omega \approx kc\gamma^2$.

To be more specific, let us define the statistical properties of the small-scale random magnetic field $\mathbf{B_{st}}$ by means of the (two-point) second-order correlation function

$$K^{(2)}_{\alpha\beta}(\mathbf{R}, T, \mathbf{r}, \tau) = \langle B_{st,\alpha}(\mathbf{r}_1, t_1) B_{st,\beta}(\mathbf{r}_2, t_2)\rangle\,, \qquad (2)$$

where $\mathbf{R} = (\mathbf{r}_1 + \mathbf{r}_2)/2$, $\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$, $T = (t_1 + t_2)/2$, and $\tau = t_2 - t_1$. Assume that the random field is statistically uniform in space and time, and take the Fourier transform of the correlator $K^{(2)}_{\alpha\beta}(\mathbf{r}, \tau)$ over spatial and temporal variables $\mathbf{r}$ and τ, which yields the spectral representation of the random field

$$K_{\alpha\beta}(\mathbf{k}, \omega) = \int \frac{d\mathbf{r}d\tau}{(2\pi)^4} e^{i(\omega\tau - \mathbf{kr})} K^{(2)}_{\alpha\beta}(\mathbf{r}, \tau). \qquad (3)$$

For the isotropic wave turbulence we find easily (Fleishman 2005)

$$K_{\alpha\beta}(\mathbf{k}, \omega) = \frac{1}{2} K(\mathbf{k}) \delta(\omega - \omega(\mathbf{k})) \left(\delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{k^2}\right), \qquad (4)$$

where $K(\mathbf{k})$ describes the spatial spectrum of the small-scale random magnetic field. The correlator (4) satisfies Maxwell's equation $\nabla \cdot \mathbf{B}_{st} = 0$, since the tensor structure of the correlator is orthogonal to the $\mathbf{k}$ vector: $k_\alpha K_{\alpha\beta} = 0$.

For the following modelling we adopt a power-law spectrum of the random magnetic field (see, e.g., Vainshtein et al. 1993; Hededal 2005):

$$K(\mathbf{k}) = \frac{A_\nu}{k^{\nu+2}},\ A_\nu = \frac{(\nu - 1) k_{min}^{\nu-1} \left\langle B_{st}^2 \right\rangle}{4\pi},\ k_{min} < k < k_{max}, \qquad (5)$$

where ν is the spectral index of the turbulence, and the spectrum $K(\mathbf{k})$ is normalized to d^3k:

$$\int_{k_{min}}^{k_{max}} K(\mathbf{k}) d^3k = \left\langle B_{st}^2 \right\rangle,\quad k_{min} \ll k_{max},\ \nu > 1, \qquad (6)$$

where $\left\langle B_{st}^2 \right\rangle$ is the mean square of the small-scale random field, $k_{min} \sim eB_{ls}/mc^2$, B_{ls} is the characteristic value of the *regular large-scale* magnetic field at the source. Therefore, the properties of the isotropic random magnetic field are described here by three main measures: rms strength of the field B_{st}, the main scale $L = 2\pi/k_{min}$, and the spectral index ν, which characterizes the distribution of the magnetic energy over spatial scales.

The radiation spectrum produced by a single relativistic particle with the Lorentz-factor γ in the presence of a regular field and the adopted small-scale random field is described by the asymptote (Toptygin & Fleishman 1987a; Fleishman 2005)

$$I_\omega = \frac{2^\nu (\nu - 1)(\nu^2 + 7\nu + 8)}{\nu(\nu + 2)^2(\nu + 3)} \frac{e^2}{c} \frac{\omega_{st}^2 \omega_0^{\nu-1} \gamma^{2\nu}}{\omega^\nu} \qquad (7)$$

at the high-frequency range $\omega \gg \omega_{Be}\gamma^2$, where $\omega_{st}^2 = e^2 \left\langle B_{st}^2 \right\rangle / (mc)^2$, $\omega_0 = k_{min}c$. Evidently, the intensity of radiation in the range between ω and $\omega + d\omega$ is specified by the energy density of the random field in the range between a corresponding k and $k + dk$. This eventually results in the spectrum $I_\omega \propto \omega^{-\nu}$ (7) with the spectral index equal to the spectral index of the random field ν in (5) (Toptygin & Fleishman 1987a; Fleishman 2005) at the frequencies larger than $\omega_{Be}\gamma^2$, where the standard synchrotron radiation decreases exponentially. Accordingly, the small-scale spatial harmonics of the random field with $k > \omega_{Be}/c$ are responsible for this spectral range, $\omega > \omega_{Be}\gamma^2$, while

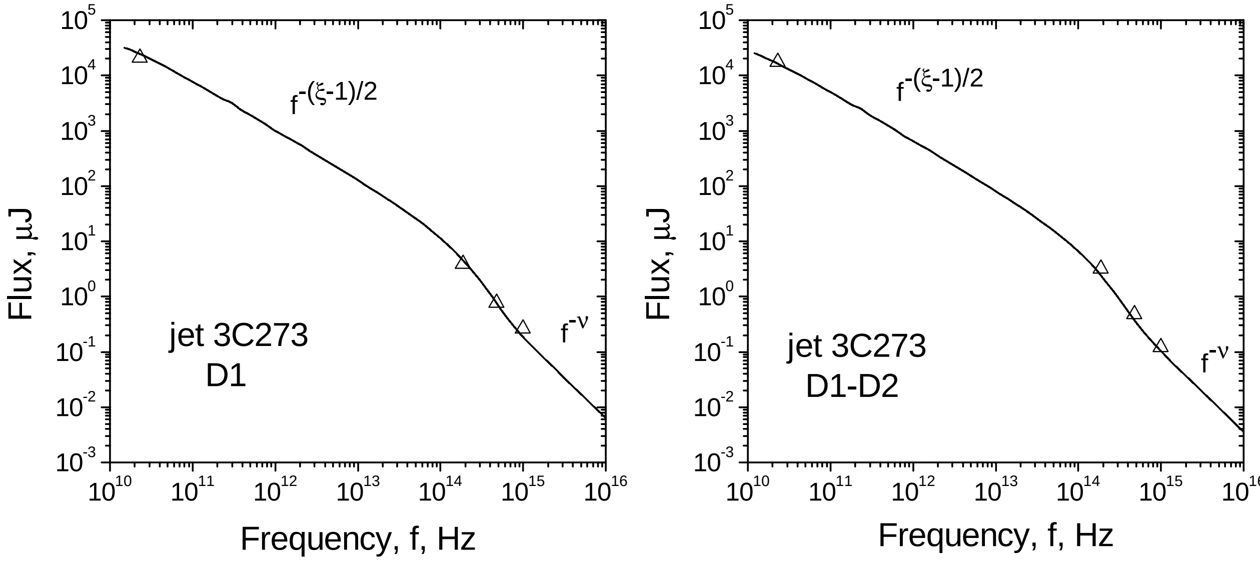

Figure 1. Radio to UV spectra (triangles) of knot D1 (left) and inter-knot D1-D2 region (right) of the jet of 3C273 from Jester et al. (2005) and model DSR spectra (solid curves) for $B_{st} = 1.2B_{ls}$ and $\nu = 1.5$. Parameters specifying radio to optical synchrotron part of the spectrum are the same as in Jester et al. (2005).

larger scale harmonics ($k < \omega_{Be}/c$) are less important, since the spectral range $\omega < \omega_{Be}\gamma^2$ is specified by standard synchrotron radiation in the regular large-scale field.

The entire radiation spectrum produced by an *ensemble* of relativistic electrons in the presence of small-scale and large-scale magnetic fields is given by integration of the single-particle spectrum (described by formulae (35) of (Toptygin & Fleishman 1987a), see also Eq. (30) in Fleishman (2005)) over the distribution of relativistic electrons over energy. We adopt a simple power-law distribution of the relativistic electrons over Lorentz-factor γ with a sharp cut-off at γ_m:

$$dN_e(\gamma) = (\xi - 1)N_e\gamma_1^{\xi-1}\gamma^{-\xi}, \quad \gamma_1 \leqslant \gamma \leqslant \gamma_m, \tag{8}$$

where N_e is the number density of relativistic electrons with energies $\mathcal{E} \geqslant mc^2\gamma_1$, ξ is the power-law index of the distribution.

Actually, the full electron spectrum in the extragalactic jets is not a simple power-law, which is evident from the turn-over of the radiation spectrum in the microwave range. However, those turn-overs can be easily interpreted in terms of synchrotron losses (Jester et al. 2005, and references therein) and are not discussed here. Therefore, we select a large enough value of γ_1, corresponding to the frequencies *above* the microwave turn-over, where the model of the simple power-law distribution (8) looks appropriate. Accordingly, the index ξ corresponds to high-energy indices as defined in (Jester et al. 2005).

For ensemble of radiating electrons with a sharp cut-off (8), the DSR contribution related to the small-scale random field will be the dominant one at the frequencies $\omega > \omega_{Be}\gamma_m^2$, where the normal synchrotron radiation from the whole *ensemble* decreases exponentially. The corresponding DSR asymptote (which may be evaluated by the integration of single particle asymptote (7) with the electron distribution over the Lorenz-factors (8)) has the form:

$$P_\omega = \frac{2^\nu(\xi-1)(\nu-1)(\nu^2+7\nu+8)}{\nu(2\nu-\xi+1)(\nu+2)^2(\nu+3)} \; \frac{e^2N_e\gamma_1^{\xi-1}}{c} \; \frac{\omega_{st}^2\omega_0^{\nu-1}\gamma_m^{2\nu-\xi+1}}{\omega^\nu}. \tag{9}$$

Although the small-scale random magnetic field is defined above by three free parameters, two of them can be substantially constrained prior to the spectrum modelling. Since only small-scale spatial harmonics ($k > \omega_{Be}/c$) are important at frequencies $\omega > \omega_{Be}\gamma_m^2$, we can adopt $k_{min} = \omega_{Be}/c \equiv eB_{ls}/(mc^2)$ or $\omega_0 = \omega_{Be}$. Then, we adopt $\nu = 1.5$ in agreement with available models of magnetic turbulence (Vainshtein et al. 1993; Hededal 2005) as well as with X-ray spectral slope for a few locations of the M87 jet (Marshall et al. 2002). Therefore, only one free parameter, the small-scale magnetic field rms strength B_{st}, is left for the purpose of the spectrum fitting.

Fig.1 displays full DSR spectra (numerically calculated with general formulae obtained by Toptygin & Fleishman (1987a)) that agree well with the optical-UV observations of one knot and one inter-knot location in the jet of 3C273. The rms value of the small-scale random magnetic field is adopted to be $B_{st} = 1.2B_{ls}$, where B_{ls} is the large-scale magnetic field, for both panels. The assumed presence of the small-scale magnetic field is, therefore, responsible for the observed flattening in the optical-UV transition, while the parameters defining lower-frequency part of the spectrum (i.e., the critical frequency of the synchrotron radiation, $f_c = 1.5f_{Be}\gamma_m^2$ (as defined in Kellerman 1964), and the electron spectral index ξ) are essentially similar to those determined in (Jester et al. 2005), since the small-scale random field has only a weak effect on the spectrum at $f < f_c$ if $B_{st} < 3B_{ls}$ (Fleishman 2005).

Similarly, Fig.2 displays DSR spectra superimposed on the observational data for two locations of the jet of M87 (Perlman et al. 2001; Marshall et al. 2002; Waters & Zepf 2005). Remarkably, the X-ray observations are apparently consistent with DSR calculated for the parameters similar to the case of the jet of 3C273 (the only minor difference is $B_{st} = B_{ls}$ in place of $B_{st} = 1.2B_{ls}$). It is important to note

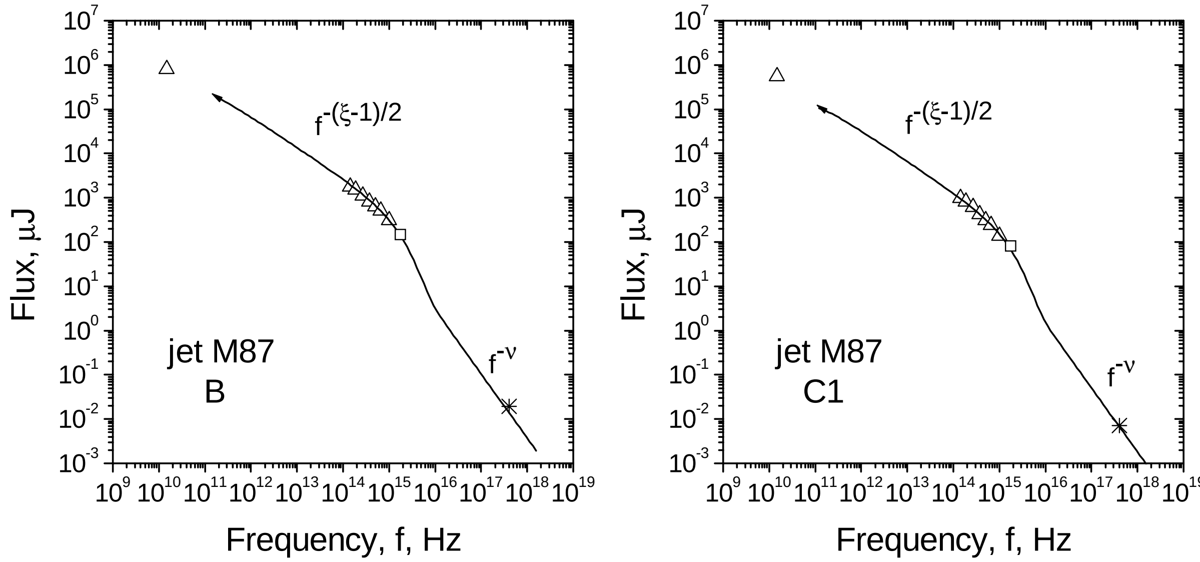

Figure 2. Radio to X-ray spectra (symbols) of knots B (left) and C1 (right) of the jet of M87 and model DSR spectra (solid curves) for $B_{st} = B_{ls}$ and $\nu = 1.5$. The radio to UV data (triangles) are taken from Perlman et al. (2001), UV data at 2×10^{15} Hz (squares) are from Waters & Zepf (2005), while X-ray data (asterisks) are from Marshall et al. (2002).

that the X-ray spectral index determined by Marshall et al. (2002) for a few spatially resolved locations, $\alpha_X \simeq 1.5$, is in excellent agreement with the standard models and observations of the turbulence spectra (Vainshtein et al. 1993; Lazarian & Beresnyak 2005; Schekochihin & Cowley 2005). We emphasize that the DSR spectrum gives equally good fits to other knots through the jets (where X-ray data is available) with the same ratio of the small-scale to large-scale field, while with varying values of the synchrotron critical frequency f_c or/and electron spectral index.

3 DISCUSSION AND CONCLUSIONS

Marshall et al. (2002), Jester et al. (2005), and Waters & Zepf (2005) compared the existing models of jet emission with the broadband spatially resolved observations of the jets of M87 and 3C273, and ruled out the one-component synchrotron models as well as inverse Compton models. They identify and clearly describe serious shortcomings of current jet models, which fail to provide a reasonable fit to the observations. In particular, Marshall et al. (2002) emphasize that the X-ray spectral slope, $\alpha_X \simeq 1.5$, typical for a few locations through the M87 jet, is inconsistent with the available models, while Perlman & Wilson (2005) propose the filling factor of the emitting material to change with frequency and location along the jet to account for the observed spectral energy distribution. In contrast, the DSR spectrum produced by a single power-law electron population in the uniform (on average) source provides excellent fits to the data in all cases considered.

The presented interpretation of the flattening of the non-thermal radiation spectra observed from spatially resolved locations in two extragalactic jets, 3C273 and M87, is self-consistent. Indeed, contemporary models of the magnetic field structure suggest that the presence of relatively strong small-scale random magnetic fields in the jet volume is likely. The most recent particle-in-cell simulations (Nishikawa et al. 2003, 2005; Jaroshek et al. 2004, 2005; Hededal & Nishikawa 2005; Hededal 2005) clearly indicate that strong small-scale inhomogeneities are efficiently generated at the shock front and exist behind the front, although the currently available numerical capacities are still insufficient to reliably track the evolution of this turbulence far away from the shock front. Nevertheless, the presence of highly enhanced level of small-scale magnetic inhomogeneities is needed for efficient pitch-angle scattering of relativistic electrons required in many models of particle acceleration. However, this elusive but important quantity has never been reliably estimated for the jet volume either theoretically or observationally.

The use of the well-established DSR theory (Toptygin & Fleishman 1987a) offers a straightforward way of estimating properties of the small-scale magnetic inhomogeneities. The synchrotron radiation spectrum produced by ultrarelativistic electrons in the jet is modified by the presence of small scale random magnetic fields. In particular, taking explicit account of the perturbations to the electron trajectories as a result of small scale magnetic fields, here referred to as DSR, yields a high-frequency power-law component to the spectrum that dominates over regular synchrotron emission above the exponential cutoff.

The proposed DSR model with only one more free parameter compared with standard synchrotron models agrees excellently with observations of these two jets if $B_{st} \sim B_{ls}$, which assumes a highly turbulent magnetic field in the jet volume. Curiously, Perlman & Wilson (2005) recently reported that spatial peaks of the X-ray flux coincide with minima of optical polarization in the M87 jet. Therefore, the presence of a tangled magnetic field (even though not necessarily with such small scales as required to produce DSR) is a favorable condition to produce X-ray emission from the jet volume, which is in qualitative agreement with the DSR

model. We emphasize that the small-scale field alone would not produce the exponential region of the radiation spectrum (Fleishman 2005), so the presence of the large-scale magnetic field is necessary.

Nevertheless, it would be highly desirable to have any additional confirmation in favor of the proposed interpretation besides the spectral fit itself, e.g., obtained from the polarization measurement. Evidently, the DSR generated in the presence of isotropic magnetic fluctuations adopted here is unpolarized emission. However, to be speculative, one may suppose some anisotropic distributions of the magnetic turbulence (Lazarian & Beresnyak 2005) given that the jets themselves are highly anisotropic objects. The polarization patterns (the position angle, the degree of polarization, and its spectral behavior) will be eventually set up by the type and strength of the anisotropy of the random magnetic field (Toptygin & Fleishman 1987b) and will be generally different from both standard synchrotron emission and inverse Compton emission, which may therefore allow a clear distinction to be made between mechanisms. One of the simplest examples of the anisotropic random field is the turbulence composed of random waves with 1d-distribution of **k**-vectors along the regular magnetic field. In this specific case the direction of the random field will be mainly orthogonal to the uniform magnetic field, which will result in the rotation of the position angle by 90^o when the transition from standard to diffusive synchrotron emission occurs as frequency increases (Toptygin & Fleishman 1987b). Although the polarization measurement needed to provide a direct test for the spectra considered in this paper is currently unavailable in UV and X-ray bands, one may try to study the polarization of the optical emission from those jets and/or jet locations that display lower value of the synchrotron high-frequency cut-off, e.g., in the IR band.

Overall, analysis of the multi-wavelength spectra from several locations along two extragalactic jets (3C273 and M87) demonstrates that the spectra considered are well described by DSR, assuming $B_{st} \sim B_{ls}$. This property may result from a saturated state of the microscopic process responsible for the magnetic field generation in the jets, e.g., from the nonlinear stage (Jaroshek et al. 2005) of the Weibel instability (Weibel 1959). In principle, this can provide us with some constraints on the jet composition. In particular, the model of Honda & Honda (2002, 2004) links the characteristic width of the current filaments (and, accordingly, the correlation scale of the magnetic field produced) with the rate of electron-positron pair production. Therefore, the ratio of the small-scale to large-scale field will differ for various regimes of the pair generation, which makes the observational measurements of this ratio of primary importance. Moreover, a precise measurement of the spectral indices of the radiation in the high-frequency range gives (potentially) direct information on the spectrum of short-wave turbulence in relativistic sources, which is highly relevant to the models of magnetic field generation and relativistic particle acceleration. We conclude that DSR from small scale magnetic fields, which are a natural outcome of current jet models, offers a plausible explanation for the observed spectral flattening in the emission from certain extragalactic jets, one which does not appeal to the presence of a secondary population of accelerated particles.

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